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Historical analysis of U.S. onshore hazardous liquid pipeline accidents triggered by natural hazards

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ABSTRACT

Incidents at U.S. onshore hazardous liquid pipeline systems were analyzed with an emphasis on natural hazards. Incidents triggered by natural hazards (natechs) were identified by keyword-based data mining and expert review supplemented by various data sources. The analysis covered about 7000 incidents in 1986–2012, 3800 of which were regarded as significant based on their consequences. 5.5% of all and 6.2% of the significant incidents were found to be natechs that resulted in a total hazardous substance release of 317,700 bbl. Although there is no trend in the long-term yearly occurrence of significant natechs, importance is found to be increasing due to the overall decreasing trend of the incidents. Meteorological hazards triggered 36% of the significant natechs, followed by geological and climatic hazards with 26% and 24%. While they occurred less frequently, hydrological hazards caused the highest amount of release which is about 102,000 bbl. The total economic cost of significant natechs was 597 million USD, corresponding to about 18% of all incident costs in the same period. More than 50% of this cost was due to meteorological hazards, mainly tropical cyclones. Natech vulnerabilities of the system parts vary notably with respect to natural hazard types. For some natural hazards damage is limited possibly due to implemented protection measures. The geographical distribution of the natechs indicated that they occurred more in some states, such as Texas, Oklahoma, and Louisiana. About 50% of the releases was to the ground, followed by water bodies with 28%. Significant consequences to human health were not observed although more than 20% of the incidents resulted in fires. In general, the study indicated that natural hazards are a non-negligible threat to the onshore hazardous liquid pipeline network in the U.S. It also highlighted problems such as underreporting of natural hazards as incident causes, data completeness, and explicit data limitations.

1. Introduction

The pipeline network in the U.S. consists of 4.3 million km of pipes, more than 300,000 km of which is transporting hazardous liquids. The majority of hazardous liquids are crude oil, refined petroleum products, and other highly volatile liquids (HVLs) that are transported from producers and processors to industrial or commercial intermediate and end users mostly via large-diameter underground steel pipes (PHMSA, 2014c). Natural hazards, such as earthquakes, floods, and landslides, can be initiating events for accidents in pipeline systems with potentially adverse consequences on the population, the environment, and the economy including major supply chains. Accidents in which the natural and technological worlds collide, leading to the release of hazardous materials, fires or explosions are commonly referred to as natech accidents (Showalter and Myers, 1994; Krausmann et al., 2011a).

Numerous severe accidents bear testimony to the risk associated with natechs related to pipeline systems. The March 5, 1987 earthquake in Ecuador (Ms 6.9) caused the destruction of more than 40 km of the Trans-Ecuadorian oil pipeline due to massive debris flows following the earthquake. Approximately 100,000 bbl oil spilled to the environment and the loss of revenue during the five months required for repair was 800 million USD, equal to 80% of the total earthquake losses (NRC, 1991). The San Jacinto River flooding in Texas, U.S. in October 1994 led to the rupture of several pipelines by the flood waters. 34,500 bbl of crude oil and petroleum products were released into the river and ignited. Besides significant environmental damage, 547 people suffered inhalation problems and burns (NTSB, 1996b). The hurricanes in 2005 and 2008 that struck the Gulf of Mexico affected not only offshore but also

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onshore facilities and severely damaged the oil and gas industry in the region including pipeline operators due to strong winds, storm surge and flooding (DoE, 2009).

The analysis of historical incident data is important for identifying the main causes, failure modes, related impacts, and statistical trends of such accidents (Montiel et al., 1996; Papadakis, 1999). This allows a better understanding of incident mechanisms and helps the preparation of prevention and mitigation measures. In the U.S., incident reports collected by the Department of Transportation's Pipeline and Hazardous Material Safety Administration (PHMSA) provide comprehensive data for this purpose (PHMSA, 2013a). Providing detailed information on natural gas and hazardous liquid pipeline system incidents, these reports can be used to identify pipeline natechs in the U.S. and to determine their dynamics and consequences. Although there are studies that evaluate the PHMSA incident data in general (Restrepo et al., 2009; Wang and Duncan, 2014), natech-specific studies do not exist.

In this study, onshore hazardous liquid pipeline system incidents reported to the PHMSA were analyzed with an emphasis on natural hazard triggers. A database-driven incident data analysis system was developed to aid the categorization and review of the incident reports. The natech incidents were identified using a keyword-based automated data-mining process followed by an expert review of the reports, which were supplemented with additional information sources. Identified natechs were analyzed statistically for long-term trends, geographical distribution, triggering natural hazard types, involved system parts, damage and impact modes, type and amount of released substances, economic costs, and other consequences.

This article describes the data collection and reviewing phases of the study, and presents the findings of the statistical analysis. The results are limited to onshore hazardous liquid transmission pipeline systems and do not cover offshore, gas, or distribution pipelines. The results of similar analyses for other pipeline systems, including European pipeline networks can be found in Girgin and Krausmann (2014, 2015).

2. Methodology

2.1. Data collection

The PHMSA administers the U.S. national regulatory program to assure the safe transportation of hazardous materials by pipeline. Regulated industries have to report loss of containment incidents which meet reporting criteria defined by the PHMSA's pipeline safety regulation (49 CFR 191/195). Incident reports include information such as location and cause of the incident, system characteristics including involved items and operating conditions, type of physical damage, type and amount of substance released, environmental and human health-related consequences, economic losses, and emergency response and remediation activities. Hazardous liquid transmission and natural gas transmission, gathering, and distribution incident reports are available since 1968 and 1970, respectively. Incidents involving hazardous liquid pipeline systems for the period 1968–2012 were covered in this study. The total number of incidents included is 11,758.

U.S. National Response Center (NRC) hazardous substance spill reports were utilized to supplement PHMSA data. NRC is the point of contact for reporting all discharges of dangerous substances into the environment in the U.S (NRC, 2013). More than 800,000 NRC reports covering the period of 1982–2012 were included in the study. Reports cover spills not only from pipeline systems but also other sources, however only pipeline-related records were utilized. The included data covers date, location, involved substance, released quantity, and description of the incidents which usually includes the cause and type of system involved.

U.S. Federal Emergency Management Agency (FEMA) disaster declarations were used as natural disaster data to aid the identification of natechs (FEMA, 2013). About 3200 declarations covering the period 1968–2012 were included in the study. The included data covers the time period, location, and short description of the disasters.

The U.S. National Oceanic and Atmospheric Administration (NOAA) storm database was also used to provide natural hazard data (NOAA, 2013). The database includes storms and other weather phenomena with sufficient intensity to cause loss of life, injuries, significant property damage, or disruption to commerce. Rare or unusual phenomena that generate media attention are also covered. About 900,000 storm database records for the period 1968–2012 were included in the study.

In addition to these primary resources, scientific and technical documents, newspaper articles and on-line resources were also utilized as additional information sources for selected incidents. The collected data was stored in a relational database specifically designed for the study (Girgin and Krausmann, 2014). The database allows triggering events (natural hazards), natechs (incidents), and information sources (e.g. spill reports) to be systematically compiled and related to each other in a tree-like structure. Inter-related hazards and incidents can also be indicated (Fig. 1).

2.2. Data review

The PHMSA reports are publicly available as 4 different datasets for the periods 1968–1985, 1986–2001, 2002–2009, and 2010–onwards (PHMSA, 2013b). Because each dataset has a different format, the available data is not uniform and the data quality also varies. Recent datasets are richer in content and generally better in quality. In most of the datasets, natural hazard-related incidents are grouped under *natural force damage* in the cause section and detailed *narratives* giving insight into the incidents are also available. The PHMSA data features temperature (freeze, frost heave, thermal stress), earth movement (earthquake, subsidence, landslide), heavy rains/floods (flotation, mudslide), lightning, and high winds as sub-causes of the natural force damage cause.

For 1968–1985, the incident cause section does not include natural hazards and incident narratives are also not available. For selected incidents it was possible to identify natechs from the information provided in external references and cross checking with natural hazard records. However, a systematic classification of natechs was not possible. Consequently, only the incidents that occurred in the period 1986–2012 were further studied.

A preliminary analysis involving cross checking of incident causes with available narratives for this period showed that there are incidents which were originally not classified as natural hazard related but were actually triggered by natural hazards. To identify such incidents and determine the uncertainty of the existing data, a comprehensive data review was conducted. A data analysis system was developed on top of the study database to be able to systematically classify, review, and further analyze the available data. The analysis system provided tools for quick data query, automated data mining and classification, review and statistical analysis. It also facilitated making necessary corrections to the records, entering supplementary information (e.g. study notes, bibliographic citations, tags), and creating links between related records through user-friendly interfaces (Girgin and Krausmann, 2014).

In order to review the data, onshore incidents explicitly listed as natural hazard related were classified into a unified set of natural hazards according to designated natural hazards in the related PHMSA data fields. The remaining incidents were automatically

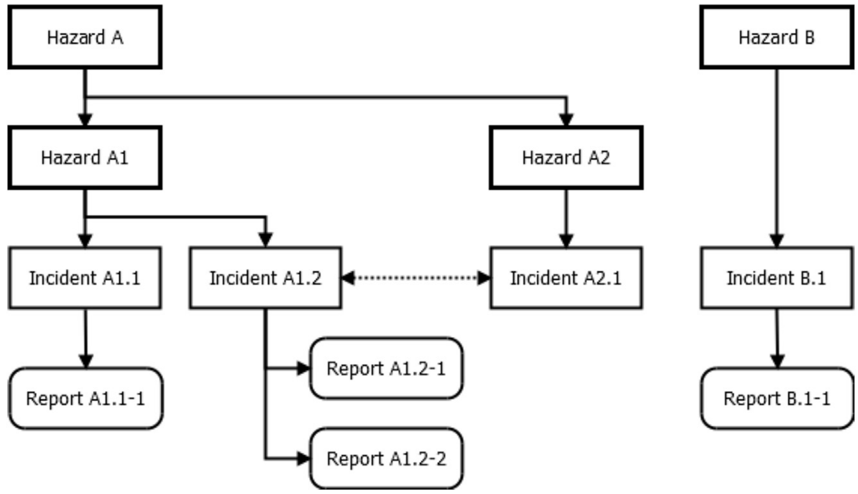

Fig. 1. Record relations in the study database.

classified by the analysis system by using a keyword-based data mining process. For this purpose, natural hazard-specific keywords were determined by examining narratives of previously classified natech incidents. Additional keywords that are synonyms of the determined keywords were collected from the WordNet lexical database (Fellbaum, 1998). All keywords were converted into keyword patterns supporting partial matching of words with wildcard characters. To classify the incidents, the system analyzed the textual contents of the incident reports to find out whether they matched natural-hazard specific keyword patterns or not. In case of a match, the natural hazard of the matching incident was set accordingly and the incident itself was designated as a natech incident. In case of multiple matching patterns, the natural hazard having the highest ranking was used. The list of natural hazards, their ranking and the complete list of keyword patterns used for the classification can be found in Girgin and Krausmann (2014).

Subsequently, all identified natech incidents were manually reviewed by at least two experts to correct possibly misclassified incidents. During this process, NRC spill reports were also automatically classified and reviewed in addition to the PHMSA data to identify the spills related to natech events. The comprehensive classification of the records allowed the analysis system to highlight possibly related records in the data sources used. This facilitated the linking of records which was carried out manually by the experts. The identified relevant NRC reports were used to supplement the matching PHMSA reports either by completion of missing information or verification of the available data. Similarly, FEMA and NOAA natural hazard records were used to clarify and verify the triggering natural hazards of the natech incidents. Furthermore, both spill and natural hazard records were also used to control incidents which were originally indicated as not natural hazard related, but having a possibility to be natural hazard related. For this purpose, all incidents which occurred in the same geographical region within a certain time period of the natural hazard records and natech-related spill reports, were identified. These incidents were reviewed manually to check for evidence of natural force-related causes or impacts. If credible evidence was found, they were classified as natech incidents. It should be noted that during the review of the NRC reports, additional hazardous liquid pipeline system incidents were identified that did not match any of the existing PHMSA incidents. Such incidents were not taken into consideration for this study.

During the review, incidents which were *triggered* by natural hazards were designated as natechs. Incidents that involve secondary causes related to natural hazards or transport of substances by natural forces that were released due to other causes were not regarded as natech incidents. However, releases due to external impacts caused by natural hazards, such as debris carried by flood waters or fallen utility poles due to strong winds, were considered as natechs. Frequently observed natural hazard contributions to non-natech incidents are sweep of released substances by heavy rain, flash flood, or storm surge, containment dam overflow or failure due to heavy rains, and hindrance of emergency response and clean-up operations.

For some incidents, it was not possible to determine with certainty the type of natural hazard trigger, although they were reported as natural force-related. In some other cases, it was not possible to assign the exact natural hazard although it was certain that the incident was caused by natural forces (e.g. reported as ground movement by natural forces). Uncertainty flags were used for such incidents in order to indicate the data reliability.

Missing data in the incident records were completed during the review from the available information in the incident narratives or by referring to other sources. Some data fields occasionally missing in the original data were geographic coordinates, involved item, type of damage, and release medium. Missing geographic coordinates were determined approximately by using address description or township/range information, if available. The U.S. National Pipeline Mapping System was used to verify the locations, where applicable (PHMSA, 2014b). Information about the release medium, which was completely missing in the dataset for 1986–2001, was completed for all natechs based on the incident narratives and NRC reports.

2.3. Data analysis

The identified onshore hazardous liquid pipeline system natechs were analyzed statistically for long-term trends, triggering natural hazards, involved system parts, pipeline characteristics, natural hazard impact and damage modes, type and quantity of released substances, release mediums, human health consequences, and economic damage.

A preliminary analysis of the long-term trend in the incident data showed that the data is not uniform through the study period and has a sudden increase in the number of incidents starting from 2002, which coincides with a change in the reporting criteria (Fig. 2). During 1986–2012, the reporting criteria were changed

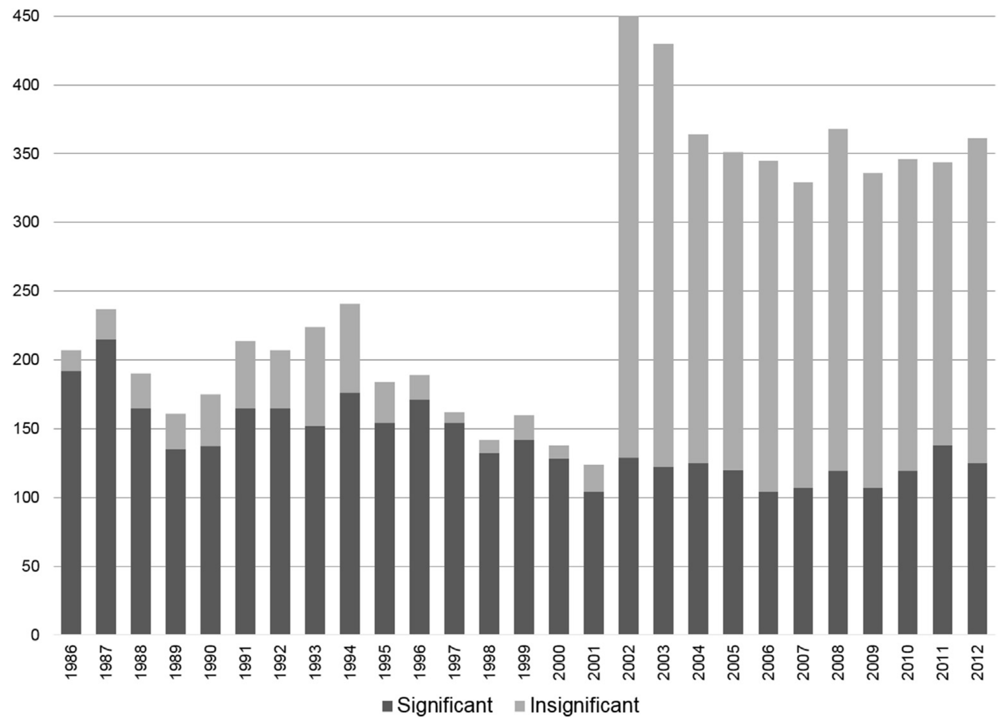

Fig. 2. Yearly trend of significant and insignificant incidents.

three times. In 1991, CO_2 was included in the list of hazardous substances. In 1994, the cost criterion for reporting estimated property damage to the operator or others was increased from 5000 USD to 50,000 USD and clean-up, recovery and product loss costs were included. Lastly, in 2002, the minimum reporting quantity was decreased to 5 gallons with special exemption conditions for spills with less than 5 bbl (PHMSA, 2011). Although the first two changes did not significantly affect the number of reported incidents, the last change increased the number about 3 fold and also changed the composition of the dataset for the last decade.

In order to eliminate the effect of changing reporting criteria and distinguish *significant* incidents, PHMSA utilizes the following criteria for long-term trend analysis:

- $\geq$5 bbl HVL or $\geq$50 bbl non-HVL release
- $\geq$50,000 USD total costs, measured in 1984 USD
- Fatality or injury requiring in-patient hospitalization
- Unintentional fire or explosion

The same criteria were used in this study to differentiate significant natechs and to obtain a consistent dataset suitable for statistical analysis (Fig. 2).

It should be noted that the actual number of significant incidents and natechs could be higher due to the under reporting of release quantities and economic cost estimates as illustrated in the following section. However, for the current analysis this is not taken into consideration and values as published by PHMSA are used unless stated otherwise.

For the analysis, 5 system part categories were used to assess the vulnerability of different parts of pipeline systems:

- *Pipeline*: line pipe including valve sites
- *Aboveground storage*: aboveground storage vessels and breakout tanks including attached equipment
- *Belowground storage*: equipment and piping related to belowground storage
- *Station*: equipment and piping related to pump and meter stations *excluding storage units*
- *Terminal*: equipment and piping related to terminals and tank farms *excluding storage units*

Because the original system part definitions were not consistent during the study period, system parts of some natechs were manually assigned based on event narratives. Cross-checks were carried out based on location information by using high-resolution satellite imagery.

In order to analyze the distribution of natechs with respect to the type of hazardous substance transported, 4 different substance categories were utilized:

- Crude oil
- Non-HVL refined and/or petroleum products which are liquid at ambient conditions
- HVL or other flammable or toxic fluids which are gas at ambient conditions
- Carbon dioxide (CO_2)

Similarly, release media were grouped under 3 main categories: *ground* (including dikes and secondary containments), *water* (including streams, channels, ponds, lakes, and bays), and *atmosphere*.

The PHMSA data provides not the actual, but estimated costs of the incident losses. As mentioned earlier, the reporting criteria considered emergency response, environmental remediation, product loss, and other costs from 1994 onwards. However, the reporting data format did not include separate fields for these costs until 2002 and only the total costs were reported in 1994–2001. Therefore, total economic losses were used for the analysis to provide a common baseline. Costs were adjusted for inflation by using annual gross domestic product price indices published by the U.S. Bureau of Economic Analysis. For reasons of consistency with the summary statistics published by PHMSA, all values were adjusted for 2013 currency by using the index data for the fiscal year 2010 (BEA, 2010).

3. Results

For a period of 27 years (1986–2012) that covered 6982 onshore incidents, 387 incidents (5.5%) were found to be natech events (Table 1). In the original dataset, only 76% of these incidents were indicated as natural hazard related. 24% of the natechs were identified by the automated classification and expert review. This indicates that the existing PHSMA incident cause descriptions do not fully represent the actual causes in case of natural hazards, resulting in an underestimation of the natech incidents. 62% of the additionally identified natechs were from the 1986–2001 period. Hence, the accuracy is higher in the later datasets.

60% of the identified natechs are among the significant incidents. Unlike for the total number of incidents, no step increase is observed in the yearly time series of the natechs (Fig. 3). The distribution of significant natechs also does not have a statistically significant trend, although an overall decreasing trend is observed in the occurrence of significant incidents (Fig. 2). This results in a slightly increasing trend in the ratio of the significant natechs to the significant incidents. As design standards, construction quality and operating practices of pipeline systems improve, other types of incidents seem to decrease in number, and incidents due to natural hazards become more important.

Data for the 2002–2012 period allows the assessment of the status of insignificant natechs. In this period, there are 94 significant and 121 insignificant natechs (Table 1). Although their number is higher, the total quantity of released substance (609 bbl) and the total cost of damage (2.7 million USD) of the insignificant natechs correspond to less than 0.5% of the significant incidents. Therefore, a detailed analysis of the consequences of natechs was carried out solely for the significant incidents. Only in certain instances reference is made to the insignificant natechs for comparison purposes. Also for the 2002–2012 period, the yearly average of the ratio of the number of significant natechs to all natechs (44%) is considerably larger than the same ratio of the incidents (33%). This suggests that natechs tend to be more severe (i.e. significant) events than other incidents in terms of consequences.

3 natechs among the incidents marked as not significant by PHMSA were found to fulfill the significance criteria according to the incident narratives. These natechs were included in the analysis as significant natechs, except for the long-term comparison of incidents and natechs.

3.1. Major natech incidents

Major natechs with respect to total economic cost and release quantity are listed in Table 2. The table covers all natechs that resulted in more than 2 million USD total economic damage or more than 2000 bbl hazardous substance release. None of the incidents in 1986–1993 have total costs high enough to be listed in the table, mainly because the costs included only the property damage. In fact, there is only one natech from this period with an adjusted reported cost greater than 1 million USD, which is the Brazos River flooding incident that occurred on June 7, 1991, near Knox City, Texas. Flooding water eroded the river bank, washed out the pipeline, and the stress of excessive water flow and debris caused an acetylene girth-weld failure releasing about 6250 bbl crude oil. The oil spread widely in the flood-plain areas over 240 km along the river. The reported costs due to property losses were 2.2 million USD, however the total cost is likely to be higher due to extensive oil-restraining and clean-up activities that took place after the incident, and which were not reported.

There are two natechs with a total cost greater than 50 million USD. The first one was due to the impact of Hurricane Katrina on a terminal facility located in Plaquemine, Louisiana on 29 August,

Table 1
Yearly summary of onshore hazardous liquid pipeline system incidents and natechs (1986–2012).

Year	Num. Incidents			Num. Significant Incidents			Sig. Total Release (10^3 bbl)			Sig. Total Cost (10^6 USD)		
	Incident	Natech	%	Incident	Natech	%	Incident	Natech	%	Incident	Natech	%
1986	207	9	4.3	192	7	3.6	276.8	6.0	2.2	27.5	1.1	3.9
1987	237	6	2.5	215	6	2.8	395.6	31.4	7.9	23.3	0.9	3.7
1988	190	8	4.2	165	5	3.0	183.8	2.2	1.2	55.4	0.2	0.4
1989	161	15	9.3	135	8	5.9	201.5	14.9	7.4	13.3	0.5	3.8
1990	175	4	2.3	137	4	2.9	122.8	4.1	3.4	24.2	0.4	1.8
1991	214	13	6.1	165	12	7.3	200.2	15.6	7.8	57.1	3.9	6.9
1992	207	7	3.4	165	6	3.6	133.8	7.6	5.7	53.4	0.1	0.2
1993	224	11	4.9	152	11	7.2	115.8	6.1	5.3	39.7	1.2	3.1
1994	241	34	14.1	176	21	11.9	159.7	57.9	36.3	88.7	52.0	58.6
1995	184	15	8.2	154	14	9.1	109.9	9.1	8.3	44.2	18.0	40.7
1996	189	11	5.8	171	9	5.3	153.6	5.9	3.8	117.7	0.6	0.5
1997	162	6	3.7	154	6	3.9	190.1	5.2	2.7	58.7	2.3	3.9
1998	142	11	7.7	132	11	8.3	139.4	3.2	2.3	71.0	6.5	9.1
1999	160	5	3.1	142	4	2.8	163.7	5.5	3.4	112.6	0.9	0.8
2000	138	7	5.1	128	6	4.7	106.3	5.1	4.8	173.3	2.8	1.6
2001	124	10	8.1	104	10	9.6	98.0	31.4	32.0	29.9	2.6	8.7
2002	453	14	3.1	129	7	5.4	95.6	0.3	0.3	58.8	0.4	0.7
2003	430	21	4.9	122	8	6.6	80.0	5.4	6.7	79.3	2.8	3.6
2004	364	21	5.8	125	11	8.8	76.3	12.2	16.0	100.9	24.1	23.9
2005	351	28	8.0	120	12	10.0	136.0	65.2	47.9	320.1	253.5	79.2
2006	345	11	3.2	104	5	4.8	135.9	0.4	0.3	63.8	7.9	12.5
2007	329	20	6.1	107	10	9.3	94.7	3.9	4.1	62.2	0.6	1.0
2008	368	22	6.0	119	6	5.0	101.0	1.9	1.8	142.8	13.0	9.1
2009	336	15	4.5	107	9	8.4	52.4	2.4	4.7	63.2	9.0	14.2
2010	346	27	7.8	119	12	10.1	99.7	4.2	4.2	1045.5	38.1	3.6
2011	344	18	5.2	138	8	5.8	88.3	7.1	8.0	269.6	149.0	55.3
2012	361	18	5.0	125	6	4.8	45.0	3.5	7.8	141.3	3.8	2.7
Total	6982	387	5.5	3802	234	6.2	3755.9	317.7	8.5	3337.6	596.3	17.9

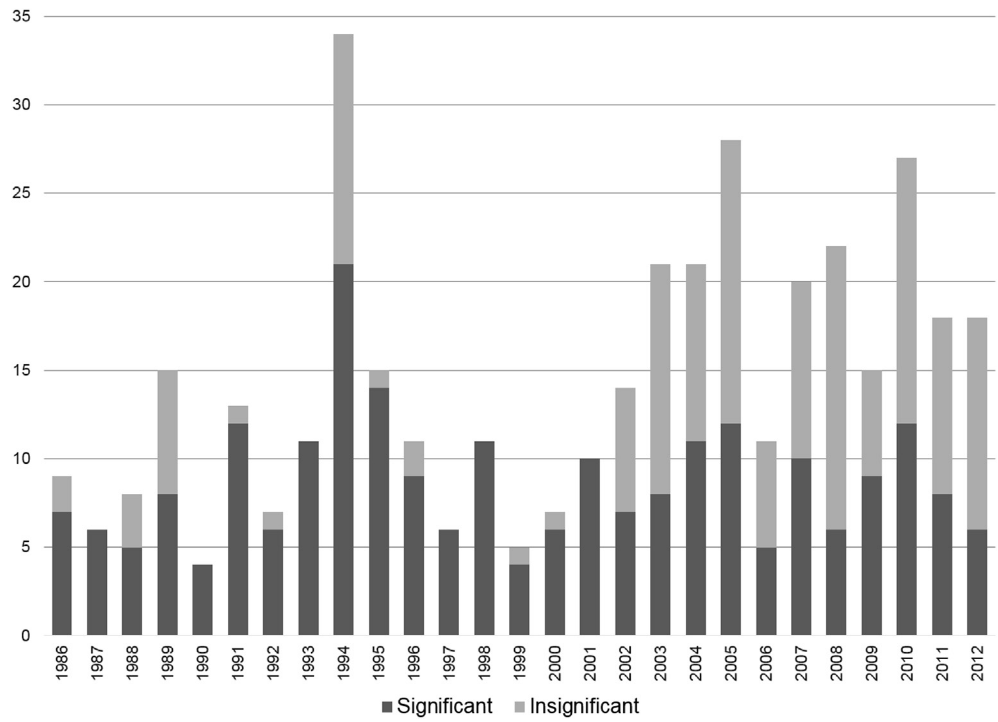

Fig. 3. Yearly trend of significant and insignificant natechs.

2005. Due to the hurricane, the roof of one storage tank was ripped off and the foundation of another was ripped out (Sever, 2006). About 23,600 bbl crude oil was spilled, most of which was contained on-site where it naturally dispersed. The rest of the oil was contained by using mechanical booms and cleaned up with skimmers and in-situ burning. The reported estimated total cost of the incident was 175 million USD. The second incident was a crude oil spill in the Yellowstone River in Laurel, Montana, which occurred on July 1, 2011. The pipeline was exposed during flood and high water conditions that persisted for more than a month and failed at the girth weld as a result of external loading caused by flood conditions (Katchmar, 2012). About 1500 bbl crude oil were spilled into the river resulting in an estimated total cost of 140 million USD. These two natechs are among the top three of the most costly pipeline system incidents from all causes within the study period. The only non-natech incident that resulted in a higher cost is the Kalamazoo River oil spill that occurred on July 25, 2010 near Marshall, Michigan, which resulted in a spill of 20,000 bbl diluted bitumen with an estimated total cost of 813 million USD (NTSB, 2001).

It should be noted that the reported costs were sometimes incomplete or inaccurate in the PHMSA dataset. For example, the cost of a pipeline rupture due to a landslide in Freeport, Pennsylvania on March 30, 1990 that resulted in the release of about 1800 bbl of mixed petroleum products into the Ohio River was reported as zero. The spilled products entered a small creek emptying into the Allegheny River and eventually the Ohio River, resulting in extensive ground and water pollution and interrupting the use of the Allegheny River as a water supply for several communities. According to the NTSB special investigation report, damage to the pipeline and environmental clean-up and restoration costs exceeded 19.5 million USD (12 million USD in 1990) (NTSB, 1996a). This cost alone is two times more than the overall reported cost of all natechs in 1986–1993. Similarly, the release of more than 2150 bbl of crude oil on October 8, 1994, into the Gum Hollow Creek that eventually entered Nueces and Corpus Christi Bays and impacted significant portions of existing freshwater and estuarine habitats, was reported to have zero cost. However, to settle two lawsuits related to the spill, the operator agreed to pay more than 66 million USD (45 million USD in 1994) (Associated Press, 2001). Solely with this figure, the incident should have been the third most costly natech in 1994–2012, however it was listed as one of the least costly ones. The uncertainty of the cost figures reported in the PHMSA dataset seems to be high, therefore they should be treated with caution.

3.2. Natural hazards

The overall distribution of significant natechs in 1986–2012 with respect to natural hazards is given in Table 3. The main natural hazard category triggering natechs is meteorological hazards with 36% contribution. Geological hazards are the second most important category with 26%, followed by climatic and hydrological hazards with 24% and 14%, respectively. Within geological hazards, subsidence is the major hazard with 32% contribution, the second being frost heave with 27%. Natechs grouped under other geological hazards were caused by rocks resting on pipelines. They are found to be significant and are more frequent than landslides. Although considered a major geological hazard for pipeline systems, there are only 6 incidents triggered by earthquakes and all of them were due 1994 Northridge Earthquake (Mw 6.7). Among meteorological hazards, lightning caused the highest number of incidents with 58% share. 20% of the incidents in this category were due to heavy rainfall, followed by storms and tropical cyclones with 7% contribution each. High winds, tornadoes, and winter storms caused the least number of incidents. As for hydrological hazards, 81% of the incidents were due to flooding and the remaining due to stream erosion/scouring during normal flow conditions. It should be noted that based on the available data it was not always possible to differentiate washouts during normal flow conditions from those during flooding conditions. Therefore, the actual distribution can be slightly different although the number of natechs under

Table 2
Major natechs with respect to release quantity and total economic cost (1986–2012).

Date	State	Substance	Natural Hazard	System Part	NPS	Man. Year	Failure Mode	Damage	Release Medium	Fire	Release (10^3bbl)	Cost (10^6USD)
1986/09/07	TX	Petr. Cond.	Str. erosion	Pipeline	8″	1965	External impact	Weld failure	Stream	No	3.0	<0.1
1987/05/30	OK	Crude Oil	Flood	Pipeline	24″	1949	Washout	Weld failure	Stream	No	19.2	0.6
1987/06/29	CO	NGL	Subsidence	Pipeline	10″	1981	Ground shift	Pipe failure	Air	No	10.0	<0.1
1989/06/07	OK	Fuel Oil	Flood	Pipeline	8″	1946	Ext. loading + Debris imp.	Weld failure	Stream	No	2.7	0.1
1989/06/13	TX	NGL	Flood	Pipeline	6″	1968	Debris impact	Pipe failure	Stream	No	10.5	0.2
1991/06/07	TX	Crude Oil	Flood	Pipeline	10″	1946	Washout > Debris impact	Weld failure	Stream	No	6.2	2.2
1991/06/14	OK	Crude Oil	Lightning	Station	–	1962	Direct hit	Overflow	Ground	No	5.3	<0.1
1992/02/06	NE	Gasoline	Freeze	Storage	–	1957	Ice expansion	Nipple failure	Dike	No	2.9	–
1992/07/10	TX	Crude Oil	Lightning	Pipeline	10″	1927	Eq. malfunc. > Overpressure	Weld failure	Ground	No	3.0	<0.1
1993/07/26	NE	Ammonia	Flood	Pipeline	6″	1968	Debris impact	Pipe failure	Stream	No	2.2	0.2
1994/01/17	CA	Crude Oil	Earthquake	Pipeline	10″	1925	Ground movement	Rupture	Stream	No	4.2	17.5
1994/01/17	CA	Crude Oil	Earthquake	Pipeline	10″	1925	Ground movement	Circum. rupture	Ground	No	0.6	2.3
1994/01/17	CA	Crude Oil	Earthquake	Pipeline	10″	1925	Ground movement	Circum. rupture	Ground	Yes	0.6	2.3
1994/01/21	KS	Diesel Fuel	Frost heave	Pipeline	8″	1929	Ground movement	Rupture	Stream	No	3.9	3.4
1994/09/11	TX	Kerosene	Heavy rain	Storage	–	1977	External load	Deflected roof	Contain.	No	5.0	<0.1
1994/10/08	TX	Crude Oil	Lightning	Pipeline	10″	1948	Direct hit	Pipe failure	Bay	No	2.2	–
1994/10/20	TX	Gasoline	Flood	Pipeline	40″	1979	Washout (new bed)	Rupture	Stream	Yes	20.0	14.6
1994/10/20	TX	Diesel Fuel	Flood	Pipeline	36″	1962	Washout (new bed)	Pipe failure	Stream	Yes	10.0	–
1994/10/21	TX	Crude Oil	Flood	Pipeline	20″	1948	Washout (new bed)	Rupture	Stream	Yes	5.4	6.6
1994/12/20	LA	Gasoline	Flood	Pipeline	20″	1944	Washout	Pipe failure	Stream	No	3.2	1.5
1995/03/11	CA	Crude Oil	Flood	Pipeline	18″	1969	Washout > Debris impact	Circum. rupture	Stream	No	4.0	14.3
1995/06/07	OK	Crude Oil	Flood	Pipeline	8″	1969	Washout >External load	Weld failure	Stream	No	2.5	0.9
1996/02/08	MO	Butane	Cold weather	Pipeline	10″	1930	Temp variation	Weld failure	Air	No	3.0	0.1
1998/10/19	TX	Crude Oil	Heavy rain	Storage	–	1945	External load	Sunken roof	Stream	No	1.0	3.4
1999/11/02	MI	NGL	Other geo.	Pipeline	30″	1954	Resting rock	Dent crack	Air	Yes	5.3	0.3
2000/02/03	TX	Crude Oil	Subsidence	Pipeline	26″	1962	Ground movement	Flange failure	Ground	No	4.0	0.3
2001/04/01	ND	Ethylene	Frost heave	Pipeline	12″	1977	Ground movement	Pipe failure	Air	Yes	27.7	1.1
2001/06/09	TX	Diesel Fuel	Heavy rain	Storage	–	1948	External load	Sunken roof	Contain.	No	2.5	0.1
2003/01/26	NC	Diesel Fuel	Freeze	Station	–	1994	Ice blockage	Piping failure	Ground	No	2.1	0.7
2004/01/25	NY	Propane	Frost heave	Pipeline	8″	1963	Ground movement	Tap failure	Air	Yes	6.2	0.4
2004/09/16	LA	Crude Oil	Trop. cyclone	Storage	–	–	Direct hit	Tank damage	Gulf	No	3.1	17.7
2004/09/16	OK	Crude Oil	Lightning	Storage	–	–	Direct hit	Tank fire	None	Yes	–	2.8
2005/01/26	KY	Crude Oil	Subsidence	Pipeline	22″	1950	Ground movement	Circum. rupture	Stream	No	6.9	9.9
2005/02/01	PA	Gasoline	Cold weather	Pipeline	8″	–	Ice formation	Valve failure	Ground	Yes	1.1	5.9
2005/03/23	CA	Crude Oil	Landslide	Pipeline	14″	1950	Ground movement	Circum. rupture	Lake	No	3.4	15.8
2005/08/29	LA	Crude Oil	Trop. cyclone	Terminal	–	–	Storm surge > Ext. impact	Piping failure	Stream	No	1.3	4.1
2005/08/30	LA	Crude Oil	Trop. cyclone	Storage	–	–	High wind > Direct hit	Tank damage	Ground	No	23.6	175.4
2005/09/02	LA	Crude Oil	Trop. cyclone	Pipeline	20″	1958	Storm surge > Washout	Rupture	Stream	No	3.2	17.8
2005/09/02	LA	Crude Oil	Trop. cyclone	Storage	–	–	Direct hit	Floor damage	Stream	No	25.4	22.0
2006/06/12	OK	Gasoline	Lightning	Storage	–	1971	Direct hit	Tank fire	None	Yes	–	6.7
2007/01/29	CO	Crude Oil	Freeze	Storage	–	2006	Ice expansion	Gasket failure	Dike	No	3.1	0.1
2008/06/03	KS	Gasoline	Lightning	Storage	–	1950	Direct hit	Tank fire	None	Yes	–	10.5
2009/04/24	OH	Propane	Lightning	Pipeline	12″	1973	Direct hit	Puncture	Ground	No	0.2	2.5
2009/12/23	LA	Crude Oil	Flood	Pipeline	16″	1965	Scouring	Pinhole leak	Water	No	<0.1	4.7
2010/01/11	LA	Butane	Cold weather	Pipeline	6″	2000	Thermal stress	Pipe failure	Air	No	2.2	0.2
2010/06/12	UT	Crude Oil	Lightning	Pipeline	10″	1952	Direct hit	Pinhole leak	Stream	No	0.8	33.8
2011/07/01	MO	Crude Oil	Flood	Pipeline	12″	1990	Washout > External load	Circum. rupture	Stream	No	1.5	139.7
2011/08/13	IA	Gasoline	Flood	Pipeline	8″	1993	Washout > External load	Circum. rupture	Stream	No	0.7	7.9
2011/12/27	TX	Propane	Subsidence	Pipeline	8″	1928	Sinkhole	Weld failure	Air	No	3.3	0.2
2012/07/21	TX	Ethylene	Lightning	Pipeline	10″	1968	Nearby hit > Ext. impact	Fire impingement	Air	Yes	3.1	1.2

hydrological hazards will be the same. Within climatic hazards, freeze is the major hazard with 72% of the incidents followed by cold weather. Overall, cold weather-related hazards make up 91% of the natechs triggered by adverse climatic conditions. The remaining were due to hot weather and droughts.

In general, distribution of insignificant natechs with respect to natural hazards is similar to the significant natechs, except hydrological hazards for which all observed natechs were significant (Table 3). Freeze is the major natural hazard causing almost one third of the insignificant natechs, followed by heavy rain, frost heave, and tropical cyclones with more then 10% contributions. In addition to the insignificant incidents listed in Table 3, there are also 40 more insignificant incidents which were indicated as natural hazard-related in the PHMSA dataset. But related natural hazards could not be determined due to limited information.

3.3. System parts

The analyzed data shows that 46% of the significant natechs occurred at pipelines, i.e. at the line pipe including valve sites. Natechs involving aboveground storage units correspond to 30% of all natechs, followed by stations and terminals by 16% and 8%, respectively. Only one significant belowground storage natech was identified.

The distribution of natechs with respect to system part differs between significant and insignificant incidents. In 2002–2012, significant natechs occurred more frequently at pipelines and aboveground storage units (66%) compared to stations and terminals (34%). In contrast, insignificant natechs often took place at terminals and stations (61%) instead of aboveground storage units and pipelines (39%). The distribution of natechs with respect to system part is also highly natural hazard dependent (Table 3).

Table 3
Summary of significant natechs with respect to hazards (1986–2012).

Hazard	Num. Insig.	Num. Sig.	Total Release (10^3bbl)	Total Cost (10^6USD)	Fire	Release Environment				System Part			
						Atm.	Soil	Water	Fire	Pipeline	Storage	Station	Terminal
Earthquake	7	6	6.1	22.6	1	–	5	1	–	6	–	–	–
Landslide	1	8	10.2	19.3	–	1	2	5	–	8	–	–	–
Subsidence	2	20	27.0	3.1	–	5	12	3	–	14	1	3	1
Frost heave	14	17	41.4	7.8	3	5	11	1	–	7	2	5	3
Other geological	5	11	6.8	4.4	2	1	5	5	–	11	–	–	–
Geological	29	62	91.5	57.2	6	12	35	15	–	46	3	8	4
Heavy rainfall	17	17	10.4	11.0	–	–	12	4	1	–	13	2	2
Tropical cyclone	13	6	56.8	237.8	–	–	1	5	–	1	3	–	2
Storm	3	6	0.6	0.3	1	2	4	–	–	–	2	3	1
Winter storm	1	2	0.6	0.8	–	–	1	1	–	–	1	–	1
High wind	2	3	0.6	<0.1	–	2	1	–	–	1	–	1	1
Tornado	–	2	0.2	<0.1	–	1	1	–	–	–	1	1	–
Lightning	5	50	19.4	69.1	38	12	12	3	23	16	23	10	1
Meteorological	41	86	88.6	319.1	39	17	32	13	24	18	43	17	8
Flood	–	26	101.9	202.7	3	–	–	26	–	26	–	–	–
Stream erosion	–	6	7.9	4.9	–	–	–	6	–	6	–	–	–
Hydrological	–	32	109.8	207.6	3	–	–	32	–	32	–	–	–
Hot weather	1	3	0.4	0.1	–	–	3	–	–	–	–	3	–
Cold weather	4	11	9.7	0.8	–	2	7	2	–	6	3	1	1
Freeze	35	41	17.4	11.1	2	3	35	3	–	4	21	9	7
Drought	–	2	0.4	0.5	1	–	2	–	–	2	–	–	–
Climatic	40	57	27.8	12.5	3	5	47	5	–	12	24	13	8
Total	110	237	317.8	596.4	51	34	114	65	24	108	70	38	20

Aboveground storage units were mostly affected by meteorological and climatic hazards. The vast majority (76%) of the heavy rainfall natechs hit aboveground storage units. Incidents involving aboveground storage units were also the highest by number for freeze and lightning natechs. However, for these hazards there were also significant numbers of incidents in other system parts. Although the percentages change slightly, stations and terminals showed a similar pattern with respect to the overall distribution of the natural hazards. For these system parts, the involvement of geological hazards was around 20%. Meteorological hazards had the same frequency with climatic hazards for terminals (40%), whereas for stations they were slightly more frequent (45%). For the pipelines, geological hazards were the primary trigger with 43% share, followed by hydrological hazards and meteorological hazards with 30% and 17%, respectively. Hydrological hazards triggered natechs only at pipelines. Similarly, natechs due to earthquake, landslide, resting rock, and drought were observed only at pipelines. Subsidence events also mostly affected the pipelines, although a small number of related natechs also occurred at other system parts.

3.4. Release quantities

Significant natechs resulted in 317,700 bbl of hazardous materials releases in 1986–2012, whereas the total release of all significant incidents was 3,755,900 bbl. Therefore the overall natech contribution is 8.4%. The distribution of yearly total natech releases shows that for the majority of years the total amount was less than 10,000 bbl (Table 1). There are only 4 years with a total release greater than 20,000 bbl, which are 1987, 1994, 2001, and 2005. For all these years except 1987, natechs constituted more than 30% of the incident releases that occurred in that year.

The distribution of natechs with respect to hazard categories based on release quantities shows that hydrological hazards was the major category with 35% (Table 4). Geological and meteorological hazards had similar contributions with approximately 30% each, while climatic hazards caused only 8% of the releases. The natural hazard resulting in the highest amount of release was flooding with 101,900 bbl, followed by tropical cyclones with 56,800 bbl. Within geological hazards, frost heave and subsidence were the most significant hazards with respect to release quantities. They were also third and fourth most significant overall. Because of their low number of occurrence, high wind, winter storm, tornado, hot weather and drought incidents resulted in insignificant amounts of releases (Table 3).

Most of the natech releases occurred at pipelines with 221,300 bbl of total release, followed by aboveground storage units with 79,500 bbl. Releases from stations and terminals were found to be significantly lower. 50% of the releases from pipelines were due to hydrological hazards, followed by geological hazards with 40%. The contribution of meteorological and climatic hazards was about 5% each. In contrast, more than 80% of the releases from aboveground storage units were due to meteorological hazards. Similarly, 63% of the releases from stations was also meteorological. Hydrological hazards did not cause any release at system parts other than pipelines. Climatic hazards were about 17% and geological hazards were very minor for aboveground storage units. These hazard categories had slightly higher contributions for stations, which were 24% and 13%, respectively. Climatic hazards has the highest share at terminals with more than half of the releases, whereas meteorological hazards were about 40%. There was a minor contribution from geological hazards.

3.5. Economic damage

In the 1986–1993 period, which only included property damage, the total cost of significant natechs was 8.3 million USD, whereas for all significant incidents it was 293.9 million USD. The natech contribution for this period is 2.8%. For the 1994–2012 period, for which the data included product loss, clean-up, and recovery costs in addition to property damage, the total cost of

Table 4
Summary of significant natechs with respect to system part and hazard category (1986–2012).

System Part	Num. Significant					Total Release (10^3 bbl)					Total Cost (10^6 USD)				
	Geo.	Met.	Hyd.	Cli.	Tot.	Geo.	Met.	Hyd.	Cli.	Tot.	Geo.	Met.	Hyd.	Cli.	Tot.
Pipeline	46	18	32	12	108	87.8	14.8	109.8	9.0	221.3	54.8	58.3	207.6	7.7	328.5
Aboveground Storage	3	43	–	24	70	2.0	64.1	–	13.4	79.5	0.7	252.4	–	1.2	254.3
Pump/Meter Station	8	17	–	13	38	1.6	8.1	–	3.1	12.8	0.8	1.9	–	2.6	5.3
Terminal/Tank Farm	4	8	–	8	20	0.1	1.7	–	2.3	4.1	0.9	6.4	–	1.0	8.3
Total	61	86	32	57	236	91.5	88.6	109.8	27.8	317.7	57.2	319.1	207.6	12.5	596.4

natechs was 588.0 million USD. The total cost of all incidents for the same period was 3043.7 million USD. Therefore, the natech contribution is 19.3%. The difference in the contribution mainly originates from natechs that occurred in certain years, which are 1994, 1995, 2004, 2005, and 2011. For the majority of the years, the total natech costs are less than 10 million USD (Table 1).

Meteorological hazards were found to be the major natural hazard category with respect to economic cost and resulted in 319.1 million USD total damage. Damage due to hydrological hazards corresponded to one third of the total cost, whereas geological hazards had slightly less than 10% contribution (Table 4). Climatic hazards resulted in only 12.5 million USD total damage. Within meteorological hazards, tropical cyclones had the major contribution with 237.8 million USD, followed by lightning events causing more than 69 million USD of total damage. Almost all the costs of hydrological hazards were due to floods (202.7 million USD), which was the second most costly natural hazard after tropical cyclones (237.8 million USD). Earthquakes had the highest share within geological hazards, followed by landslides and frost heave. Among climatic hazards, freeze is the leading natural hazard with a share of 89% in terms of costs (Table 3). Almost all cost of the natechs involving aboveground storage units were due to meteorological hazards, mainly tropical cyclones. Meteorological hazards also resulted in the most damage at terminals. Among the natechs involving pipelines, the majority of the cost was due to hydrological hazards, followed by meteorological and geological hazards. Damage and losses due to climatic hazards at pipelines was comparatively not significant. However, climatic hazards were the major hazard category for stations with 50% contribution.

The analysis of detailed cost data available for 2002–2012 shows that the property damage costs correspond to only 20% of the total incident costs. Remediation (35%) and emergency response (26%) costs were more significant. However, for the natechs in the same period, the total property cost had the highest share with 46%. Costs of product loss and remediation activities were found to be insignificant but emergency response costs were high with 35%. 76% of the total property cost was due to a single natech, which was the terminal facility incident due to Hurricane Katrina in 2005 mentioned before. Apparently, for this incident all cost values except the property damage were reported as zero, which gives the impression that the total cost estimate couldn't be divided into categories and was reported as a single figure resulting in an imbalance in the cost data. If this incident is excluded, the total contribution of property damage for all natechs reduces to 14%. Overall, it can be concluded that the property costs are only a fraction of the incident costs and hence the incidents in 1986–1993 should not be considered as less significant in the economic sense due to their low total reported cost, which only include property damage.

3.6. Geographical distribution

Geographic distribution of the natechs is given in Fig. 4. The figure shows that the natechs are concentrated in a few states of the U.S. Number of significant natechs, total amount of release, and total economic damage with respect to the hazard categories for selected states are given in Table 5. The table includes the states fulfilling at least of the following criteria: $\geq$4 significant natechs, $\geq$2500 bbl of total release, or $\geq$2 million USD total economic cost. Among these states, Texas had the highest number of incidents corresponding to 27% of all significant natechs. Texas is followed by Oklahoma (10%), Louisiana (7%), California (6%) and Kansas (6%). More than half of the natechs occurred in these 5 states. Because the occurrence of incidents is also a function of the pipeline network density, it is not possible to attribute the high number of natechs solely to the natural hazard susceptibility of these states. In fact, a comparison of incident and natech occurrence ratios of the states shows that there is no significant difference between the occurrence patterns. States with the highest number of natechs also had the highest number of incidents.

The majority of the states experienced a total release of less than 10,000 bbl. There were 4 states with more than 20,000 bbl of release, which were Texas, Louisiana, Oklahoma, and North Dakota. In Texas and Oklahoma, the main hazard causing releases was flooding. For Louisiana, the triggers were almost completely meteorological involving tropical cyclones, whereas geological hazards were the main hazards in North Dakota. Geological hazards caused the main proportion of releases in California, Colorado, Georgia, Kansas, Michigan, Minnesota, Montana, Pennsylvania, and Wyoming. In addition to Louisiana, meteorological hazards were also the main release trigger in Alabama. In Iowa and Kentucky, hydrological hazards caused most releases, whereas in Missouri and Nebraska the major natural hazard contribution was from climatic hazards. While Texas has the highest number of incidents, in terms of economic losses it is outranked considerably by Louisiana (247 million USD), Montana (141 million USD), and California (55 million USD). The economic damage experienced in Texas was only 42 million USD, which was mainly due to hydrological and meteorological hazards. It is followed by Utah with 34 million USD damage, all due to meteorological hazards. These 5 states altogether constituted about 88% of the total natech cost. Meteorological hazards were the main contributor in Kansas and Oklahoma. In Kentucky and Iowa, most of the economic losses was due to the hydrological hazards, whereas in Pennsylvania it was climatic hazards.

3.7. Substance type

47% of the natechs by number involved the release of crude oil, followed by non-HVL and HVL incidents with 35% and 17% contributions, respectively. CO_2 related incidents were only 1% of all natechs. Because the lengths of the pipeline systems of different substances are not equal, a direct comparison of the number of incidents is not feasible. Mileages by hazardous liquid category are available only starting from 2004 (PHMSA, 2014a). Therefore, a historical comparison of annual incident rates for different substance categories is not possible for the whole study period. However, taking the time-series of the annual mileage for the

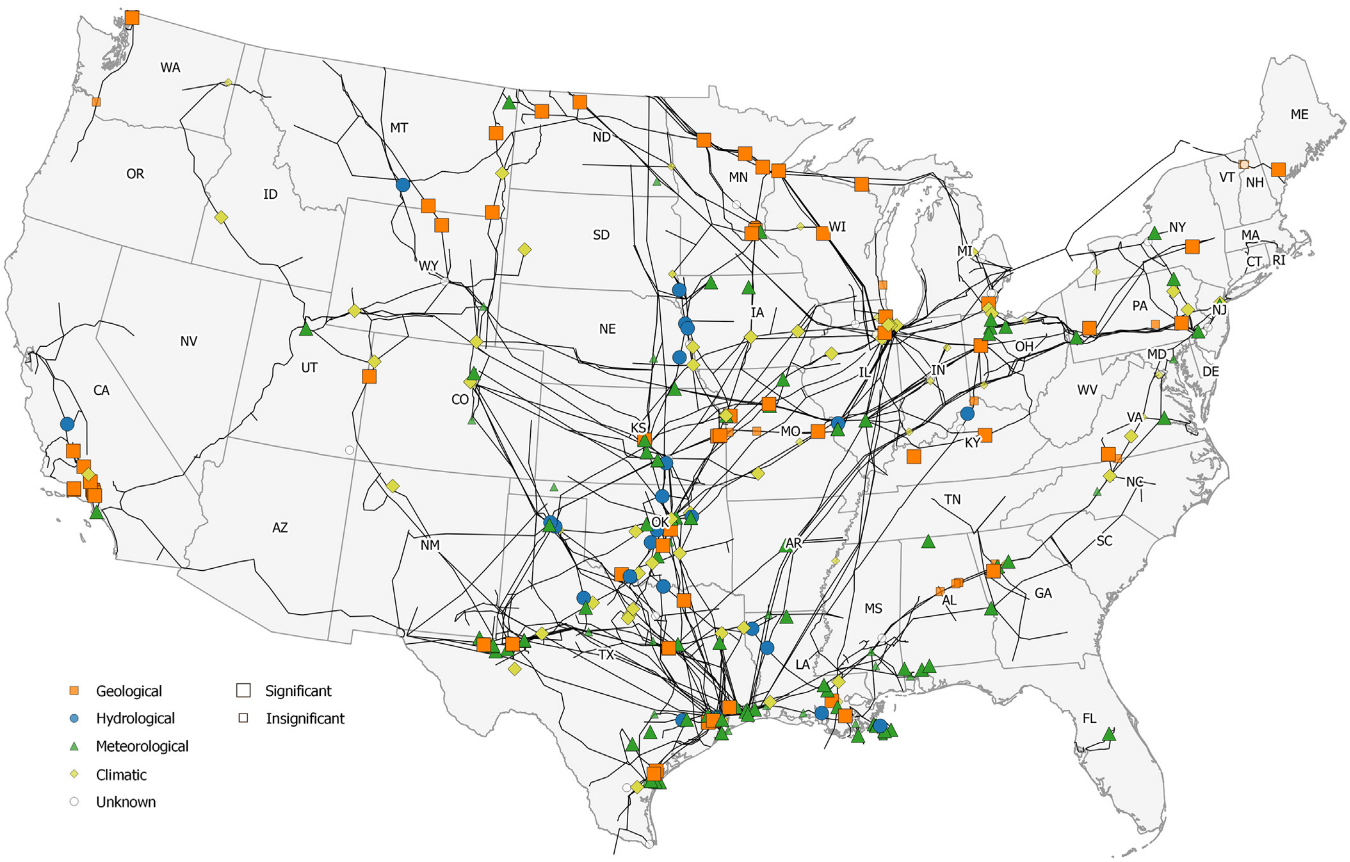

Fig. 4. Geographical distribution of natech incidents (1986–2012).

whole hazardous liquid pipeline network into consideration and using the proportional mileage information for different substance categories in 2004–2012 as a reference, average annual natech occurrence rates per 1000 km of pipeline are estimated as 0.053, 0.032, 0.018, and 0.024/year /10^3 km for crude oil, non-HVL, HVL, and CO_2 pipelines, respectively. The overall value for all natechs is 0.034/year /10^3 km for 261,275 km average annual length of the hazardous liquid pipeline network in the U.S.

A comparison of significant and insignificant natechs in the period 2002–2012 showed that the percentages insignificant

Table 5
Regional summary of significant natech incidents (1986–2012).

State	Num. Significant					Total Release (10^3 bbl)					Total Cost (10^6 USD)				
	Geo.	Met.	Hyd.	Cli.	Tot.	Geo.	Met.	Hyd.	Cli.	Tot.	Geo.	Met.	Hyd.	Cli.	Tot.
Alabama	–	4	–	–	4	–	0.6	–	–	0.6	–	1.8	–	–	1.8
California	11	1	1	1	14	11.5	<0.1	4.0	0.2	15.7	40.4	0.7	14.3	0.1	55.5
Colorado	1	1	–	3	5	10.0	<0.1	–	3.5	13.5	<0.1	0.1	–	0.1	0.2
Illinois	2	3	1	5	11	0.3	2.1	0.1	0.8	3.3	<0.1	3.0	–	0.8	3.8
Iowa	–	2	3	4	9	–	0.3	1.3	0.8	2.4	–	0.5	8.0	0.7	9.2
Kansas	3	6	2	3	14	5.6	0.5	2.1	1.5	9.6	3.6	10.6	<0.1	0.3	14.5
Kentucky	2	–	1	–	3	1.8	–	6.9	–	8.7	0.5	–	9.9	–	10.4
Louisiana	2	9	4	2	17	0.1	56.9	3.6	2.2	62.9	0.2	239.9	6.3	0.4	246.7
Michigan	2	–	–	2	4	5.3	–	–	0.2	5.5	0.5	–	–	0.4	0.8
Minnesota	7	1	–	–	8	2.9	0.5	–	–	3.4	2.8	0.2	–	–	3.0
Missouri	3	2	–	1	6	1.4	0.2	–	3.0	4.6	0.3	<0.1	–	0.1	0.4
Montana	3	1	1	1	6	2.9	0.1	1.5	0.4	4.9	1.3	<0.1	139.7	<0.1	141.1
Nebraska	–	–	2	2	4	–	–	2.3	3.0	5.3	–	–	1.2	<0.1	1.2
New York	1	1	–	–	2	6.2	0.1	–	–	6.3	0.4	0.4	–	–	0.7
N. Dakota	2	–	–	–	2	27.7	–	–	–	27.7	1.6	–	–	–	1.6
Ohio	1	4	–	1	6	0.1	0.3	–	0.3	0.6	0.1	2.7	–	<0.1	2.8
Oklahoma	3	7	7	8	25	1.6	5.8	29.4	2.1	38.9	0.4	10.9	2.6	0.1	14.0
Pennsylvania	2	3	–	2	7	1.8	<0.1	–	1.3	3.1	0.1	0.2	–	7.2	7.6
Texas	9	34	10	10	63	11.0	20.4	58.6	4.6	94.6	1.9	13.3	25.6	1.1	41.9
Utah	–	1	–	–	1	–	0.8	–	–	0.8	–	33.8	–	–	33.8
Virginia	2	1	–	1	4	0.1	<0.1	–	<0.1	0.1	0.2	<0.1	–	0.1	0.3
Wyoming	1	–	–	3	4	0.7	–	–	0.5	1.2	0.7	–	–	0.1	0.8
Total	57	80	33	49	219	91.0	88.6	109.8	24.4	313.7	55.0	318.1	207.6	11.5	592.1

natechs were around 60% for crude oil and non-HVL incidents. However, HVL natechs tend to be more significant (75%) rather than insignificant (25%) by number. 46% of the HVL natechs involve gasoline, whereas 39% involve other liquid fuels such as diesel, fuel oil, kerosene, and jet fuel. 8% of the released substances are mixture of refined products (e.g. transmix) and the remaining 7% includes other non-HVL products. Among HVLs, liquefied petroleum gases (LPG) and natural gas liquids (NGL) are the most frequently observed released substances with a combined 85% contribution. 10% of the HVL natechs involve anhydrous ammonia and the remaining 5% are other HVLs.

3.8. Pipe characteristics

Nominal pipe sizes of the pipelines affected by natural hazards show a right-skewed distribution. 32% and 20% of the natechs occurred at 8″ and 10″ pipes respectively, while the majority with 74% were between 6″ and 12″. The number of natechs was very low for all pipe sizes between 12″ and 40″, except 24″ and 26″ which has a slight increase. There is no observable difference between the pipe size distributions for different natural hazard categories, except climatic hazard related incidents which were not observed in the pipelines above 10″. The situation was also similar with respect to substance type.

The distribution of the pipe age of the natechs involving pipelines is slightly right skewed towards the pipes aged between 20 and 29 years with a distribution mean of 40–49 years. The number of natechs involving very old (≥70 years) and relatively new (<20 years) pipes are low. The majority of the pipes involved in natechs are in the age range of 20–49 years. In general, pipe age distributions with respect to natural hazard categories are not found to be different and exhibit the same shape. With respect to substance type, incidents involving crude oil have occurred comparatively more frequently in older pipes, whereas non-HVL and HVL incidents involve medium aged and relatively new pipelines, respectively.

3.9. Release medium

48% of the natechs resulted in releases to the ground including into dikes and secondary containments. Releases to inland water bodies and sea correspond to 28%, whereas releases to the atmosphere were 14%. The released substance was directly consumed by fire in the remaining 10% of the natechs, resulting in zero net release to the environment (Table 3). Hydrological hazards resulted in releases only to the water environment, which was in most of the cases streams. For climatic natechs the major release medium was ground. Although for geological and meteorological natechs the main release medium was also ground, atmospheric releases and spills to water bodies were also common. All natechs with zero net release due to fire consumption were meteorological, more specifically lightning incidents, except one case which was related to heavy rain (Table 3).

With respect to system part, incidents involving body of pipe resulted mainly releases to water bodies with 50%. For other system parts release to the water were minor and the main release medium was the ground. For aboveground storage tanks the second release type was zero net release with 30% contribution while atmospheric releases were very rare. With respect to substance type, crude oil and non-HVL substances show a similar pattern in which the majority of the releases were to the ground, followed by about 30% of releases to water, and the remainder with zero net release. All HVL releases were to the atmosphere, except for 22% of the releases that occurred at river crossings.

3.10. Damage and impact modes

About 55% of the natechs involving pipelines resulted in pipe rupture, whereas the remaining 35% and 10% were leaks and component failures at valve sites, respectively. Ruptures were dominant for hydrological and geological hazards, while leaks were more frequently observed for meteorological and climatic hazards. All earthquake and landslide natechs, and the vast majority of flood and subsidence natechs resulted in ruptures. In contrast, all resting rock and the majority of the lightning natechs involved leaks. For other hazards, such as storm, tropical cyclone, freeze, and drought, the numbers of incidents was insufficient for drawing statistically meaningful conclusions.

The observed impact modes of natural hazards on different pipeline system parts are diverse and highly specific to the type of natural hazard. Although the PHMSA dataset includes natechs triggered by various natural hazards, it does not cover all natural hazard-related damage and impact modes (Hann et al., 1997). Frequently encountered natech damage and impact modes are as follows:

All earthquake-related failures, which were due to the 1994 Northridge Earthquake, were ruptures and cracks at acetylene welds of a pipeline constructed in 1925. The failures are attributed to the welding method and inadequate construction standards of the time. In fact, two other pipelines exposed to the same earthquake forces in the epicenter area, which were constructed after 1950 with better welding methods (arc welding), did not sustain any damage (NIST, 1997). The impact mode of rocks resting on pipelines was denting followed by pinhole leaks or hairline cracks. In some cases rocks were moved underneath the pipelines by ground movement due to frost heaving.

All heavy rain natechs at stations and terminals involved sump overflow due to rain waters and flash floods. Heavy rain-related natechs that affected aboveground storage units were usually caused by excess pressure exerted on floating roofs due to accumulated rain water. Partially or completely sunken roofs were common. Although they were seldom, tank floatation resulting in tank bottom failure was also observed. All storm natechs involved electrical storms which resulted in equipment failure or malfunction due to power loss or electromagnetic influence. Releases were generally in the form of sump/tank overflow due to pump or control equipment-related problems, or leaks and ruptures due to overpressure caused by malfunctioned control or relief systems. In case of winter storms, the observed impact mode was snow weight. In one case, accumulated snow caused the floating roof of an aboveground storage tank to sink and in the other case it resulted in the failure of a fitting. The impact modes observed in high wind natechs were impact of debris (e.g. boards) carried by the winds and the falling of nearby structures (e.g. power poles) due to excessive wind forces. Similar impact modes were also observed for tornadoes. Tropical cyclones involved combined effects of heavy rain and wind events. More structural damages were observer due to stronger forces exerted during cyclonic conditions. Lightning natechs involve tank fires due to direct hit of aboveground, mainly floating roof, storage tanks, small leaks from pinholes due to electrical arcs, equipment failure/malfunction due to direct hit or power loss due to nearby hit. Equipment-related damages usually resulted in overpressure in the pipeline system and subsequent pipe rupture at a different location.

Natechs due to hot weather were caused by thermal stress and sun pressure. Cold weather-related natechs were also mainly due to thermal stress, usually caused by significant temperature variations. Four impact modes were identified for freeze natechs, which are ice expansion (74%), ice formation (13%), falling ice/snow (8%), and frozen components (5%). Expansion of ice during freezing was the most prevalent impact mode and generally caused cracks in the components. Ice formation was found to have caused component malfunction and blockage of auxiliary pipes. Water naturally present in the transported substance is the main source of ice, but residual water from hydro-testing of the pipeline system also caused several incidents. Falling ice/snow resulted in cracks at the pipeline system components, whereas freeze mostly caused component malfunction leading to releases. Two natechs involving drought occurred in December, 1995 near Palo Pinto, Texas. Extended drought conditions allowed the ground to shift, causing collar joint failures along the same pipeline at different dates.

3.11. Human health

There were no fatalities due to natechs in 1986–2012. 1851 injuries were reported due to three pipe breaks during the San Jacinto River flooding near Harris, Texas on 20 October, 1994. However, the NTSB incident investigation report indicates that only 547 people received injuries (NTSB, 1996b). The injuries were due to the significant amount of petroleum product that caught fire and moved downstream with the flooded stream. They were minor smoke and vapor inhalation complaints, except two cases that involved serious burns. Probably due to the discrepancy in the reported numbers, the total number of injuries of these three events are excluded from the official PHMSA summary statistics (PHMSA, 2014d). One person was injured due to the crude oil spill after the Northridge Earthquake in the City of San Fernando into the Los Angeles River that caught fire on its course along the river. This injury is also mentioned in the NIST report related to lifeline performance and post-earthquake response (NIST, 1997). Although it was not numerically indicated in the incident data, the narrative of a petroleum condensate spill due to stream erosion that occurred on September 7, 1986 at the Red River crossing near Cooke, Texas, mentions about medical treatment of about 14 people. Newspaper articles on that day also support this information (Associated Press, 1986).

17 natechs were reported to have involved evacuations of the public, residential areas, and schools nearby the incidents. It is not possible to give an exact figure because the number of evacuees was not provided in all cases, but about 1000–1500 people are estimated to have been evacuated due to natechs.

3.12. Fire and explosion

There are 51 natechs which resulted in fire (Table 3). 75% of the fire incidents were due to lightning and the contributions of other natural hazards were comparatively insignificant. Lightning incidents also differ from other natechs with a very high frequency of ignition, which is also observed in gas pipeline networks (EGIG, 2011). The occurrence of fires did not show any dependency with respect to substance type. However, they occurred more frequently at aboveground storage tanks (45%) and pipelines (31%). In addition to fires, explosions were also reported for 11 natechs. However, the available incident narratives do not include any information about explosions in more than 60% of these incidents although these incidents were flagged as explosion related in the PHMSA dataset.

4. Discussion

The analysis of the identified natechs showed that natural hazards are a non-negligible threat to onshore pipeline systems transporting hazardous liquids in the U.S. Although they occurred less frequently than incidents from other causes, their consequences are comparatively more serious than the other incidents as shown by the high amount of economic damage despite a notably lower natech incidence. A higher ratio of significant natechs to all natechs compared to the ratio of significant incidents to all incidents also supports this conclusion.

The significant number of natech incidents additionally identified during the review indicates that there was a tendency to under-report natural hazards as causes of incidents. Although natural hazards can be indicated as causes in the incident reporting forms, incidents triggered by natural hazards are not always properly reported as natural-hazard related. Although for some cases it is difficult to correlate incidents to natural hazards, some misclassification can be solved by providing proper guidance.

The analysis showed that natural hazards do not impact all pipeline system parts equally and some parts are more susceptible to specific natural hazards. Damage and impact modes were also significantly different for different system parts, especially if the impacted item is a component like a valve, pump, or control equipment. Therefore, while studying the natural hazard impact on pipeline systems, different system parts should be addressed separately, especially if the study involves the historical analysis of incident data including consequences.

Aboveground facilities of pipeline systems, especially aboveground storage tanks, have common design and components to their counterparts at other industrial plants such as refineries. Therefore the natech susceptibility and observed natech-related damage modes are also not different. In addition to the incident data originating from pipeline systems, which is limited in extent, more widely available incident data from fixed industrial plants can be used to obtain more detailed information for such system parts (Renni et al., 2010; Cozzani et al., 2010; Girgin, 2011; Krausmann et al., 2011b; Cruz and Krausmann, 2013).

Earthquakes are generally regarded as a major threat to pipeline systems, but the analysis shows that they rarely triggered accidents in the U.S. hazardous liquid pipeline network. There is only one triggering earthquake over a period of 40 years and it affected solely a single pipeline system. Well established design criteria, proper construction methods, and appropriate protection measures are presumably the reasons for the good earthquake performance. The Trans-Alaska Pipeline System can be considered as a good example, which suffered only minor damage and no spill during the 2002 Denali Earthquake (MW 7.9) although the fault rupture crossed the pipeline within a 500 m corridor and caused a shift of about 4 m horizontally and 0.75 m vertically (USGS, 2003).

Besides directly triggering incidents, natural hazards can also aggravate incidents by accelerating other causes, facilitating or initiating transport of spilled materials that would otherwise stay contained in a small area, or hindering response, recovery, and clean-up operations which could otherwise happen more quickly. Especially major natural disasters, such as tropical cyclones, may result in competing resource needs for response activities. These aggravating factors should also be considered while assessing natural hazard impacts on pipeline systems.

Slow onset hazards and the time variant nature of some natural hazards should be considered properly during the operational life of pipeline systems, which is typically very long. In the U.S., there are operational pipelines which were built over 100 years ago. Even if natural hazard risks were considered at the time of the design and construction of these systems, changes in the regional natural hazard risks are very likely due to the large geographical extent of the systems and also global factors, such as climate change. Therefore, risk assessments and associated mitigation measures should be periodically reviewed. This process should be regulated by competent authorities, especially for pipelines passing through high natural-hazard risk zones.

Besides data availability, data quality and explicit data limitations are equally important and should be carefully evaluated. Even if long-term incident data is available, different reporting criteria used during the period can create a bias in the data that needs to be considered in the analysis. Although named similarly, exact definitions of some data elements can also be different over time and prevent overall clustering or aggregation. Ambiguities in the total economic cost data due to changes in the PHMSA reporting criteria is an example of this problem. The lack of specification of natural hazards as a cause in the 1968–1986 PHMSA data can also be given as another example.

Following an incident, certain information, such as environmental consequences and economic costs, cannot be obtained quickly. In case of natechs, aggravating conditions due to the triggering natural hazard may even hinder the collection of primary information. However, data actuality and completeness is crucial for a proper analysis and should be ensured by all responsible parties. Pipeline operators should periodically update and complete incident reports if previously unknown or more accurate information becomes available, and competent authorities should encourage and actively follow this process. Incomplete or outdated information is difficult to recognize by third parties, hence it cannot be filtered out easily from the analysis and may result in erroneous conclusions. Cost estimates in the PHMSA data, which appear to be significantly underestimated for earlier time periods, are an example.

During the study, a database and an analysis system were developed for the systematic collection, classification, and statistical analysis of natech data related to pipeline systems. The database, which is more complete than the original PHMSA dataset due to data supplements from other sources in the course of this study, is especially useful for providing case-specific natech data that is scarce in the scientific literature and existing accident databases. Although PHMSA data is limited to the U.S., further analysis with respect to accident mechanisms and consequences will benefit the safety of pipeline systems also in other parts of the world where similar natural hazards are common.

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